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AN ALTERNATIVE VIEW OF FLAT ROTATION CURVES OF SPIRAL GALAXIES

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RESUMEN

El presente panorama de la interpretación de las curvas planas de rotación en las espirales, se apoya en la necesidad de una componente de masa obscura para forzar hacia arriba la curva de rotación que se obtiene combinando la materia luminosa en la galaxia con un cociente masa luminosidad semejante al de la vecindad solar.

Las relaciones masa luminosidad obtenidas en los estudios de galaxias binarias son alrededor de diez veces mayores que los valores supuestos para galaxias espirales (Schweizer 1987; Soares 1989). Si se consideran tales valores de M/L como los valores reales en espirales, ésto implica que la curva de rotación kepleriana derivada mediante la combinación de estos valores M/L con la distribución de materia luminosa de una galaxia espiral, queda por encima del perfil rotacional observado. Aquí se argumenta que un procedimiento más coherente y convincente es buscar el parámetro físico responsable de disminuir la curva de rotación predicha hasta el nivel observado.

Debido a las consideraciones anteriores, se ha propuesto un modelo, basado en la existencia de una significativa fuerza de flotación en el disco gaseoso de galaxias espirales. El modelo tiene una contraparte plausible fenomenológica y predice un rango amplio de curvas de rotación incluyendo las que son planas.

ABSTRACT

The present view of flat rotation curves of spiral galaxies relies upon the necessity of a dark mass component to *push up* the predicted declining portion of the rotation curve, that arises when the galaxy luminous matter and mass to light ratios similar to the ones in the solar neighbourhood are combined.

Mass to light ratios obtained from binary galaxy studies are about ten times as large as the values currently assumed for spiral galaxies (Schweizer 1987; Soares 1989). Considering them as the real M/L for spiral galaxies, it implies that the Keplerian rotation curve derived by the combination of these M/L values and the luminous matter distribution of a spiral galaxy lies *above* observed rotational profiles. Here we argue that a more convincing and coherent approach is to search for the physical processes responsible for *pulling down* such a predicted rotation curve to the observed levels.

Accordingly, a toy model is proposed based on the existence of significant buoyancy forces in the gaseous disk of spiral galaxies. The model has a plausible phenomenological counterpart, and predicts a wide range of rotation curve shapes including flat ones.

Key words: **DARK MATTER – GALAXIES-ROTATION CURVE – GALAXIES-SPIRAL**

I. INTRODUCTION

The shape of spiral galaxy rotation curves exhibit a distinct feature in the outer region of galaxies, namely, the flatness of the constancy of the circular velocity as a function of radius (see van Albada and Sancisi 1986, for a review). Inside the luminous part of galaxies the rotation curves can be explained by a combination of matter distribution with constant mass to luminosity ratios. The M/L values so obtained agree well with acceptable values for the M/L in the solar neighbourhood. In the outer regions the luminous rotation curve declines in a Keplerian way ($V \propto r^{-1/2}$), but the observed rotation curve, usually obtained from the 21-cm line of neutral hydrogen gas, remains constant, and requires the assumption of a dark matter component (a dark halo) in the mass distribution to be fully accounted for. Thus, the dark halo hypothesis is necessary to *push up* the rotation profile derived from the luminous matter alone. It is clear that the whole dark mass hypothesis relies heavily on the assumption that local M/L values, in the Galaxy, are in general valid for an entire and any spiral galaxy. We argue here that this is a very strong assumption, and point to another direction.

The presence of dark matter has been invoked in a variety of astronomical systems (e.g., elliptical galaxies, groups and clusters of galaxies). Here we are solely interested in the case of individual spiral galaxies, which are largely recognized as the strongest support to the dark matter hypothesis (Trimble 1987; Sanders 1990), and that constitute a well-defined class of gas-rich, axisymmetric, and rotationally supported objects. The model galaxy discussed in the following section is meant to address this specific class.

The reliable M/L values for individual galaxies should be those values obtained from a dynamical study of spiral galaxies considered as units, i.e., in studies of binary galaxies. Such systems have been the subject of extensive investigations in the past decades. Recent binary galaxy studies imply that the M/L values for individual spiral galaxies are as large as ten or more times the local solar M/L (Schweizer 1987; Soares 1989), figures that are not ruled out by stellar population synthesis of spiral galaxies (Valentijn 1989). With these results, it is obvious that a luminous disk leads to a rotation curve that is located *above* the observed rotation curves of spiral galaxies, and that the relevant question turns out to be whether there is a physical process that has *pulled down* the predicted rotation curve to the observed pattern.

We assume that the real M/L values of spiral galaxies are those obtained from binary studies ($M/L_B \approx 40$, $H_0 = 75$ km s^{-1} Mpc^{-1}), and propose a model that is capable of pulling down the Keplerian rotation curve derived from such M/L value coupled to the observed luminous profile of spiral galaxies. The model is based on conventional Newtonian dynamics and on intrinsic properties of spiral galaxies.

II. MODEL GALAXY

a) *The Buoyancy Potential*

Let us now describe a kind of toy model for the effective potential of a spiral galaxy. Later we present a possible phenomenological description of the same model. The effective gravitational potential of a disk galaxy is described by

$$U(r) = \frac{GM}{r}\left(1 + \beta e^{-r/r_0}\right) , \qquad (1)$$

where β and r_0 are intrinsic galactic scale parameters (in principle different from galaxy to galaxy), and where, for simplicity, we assume that M is the bulk of the total galactic mass and is located at the center of the galaxy. M does not include the mass of the gaseous component of the galactic mass distribution since we know that it is small compared to the total mass of a spiral galaxy.

This potential has a component of the Yukawa type, that we identify as a "buoyancy" component. That is to say, any body (with a length-scale l) immersed in a gaseous disk (the galactic disk, with radius $R \gg l$ at a position r from the center of the disk is subjected to the gravitational attraction due to the galaxy mass plus an additional buoyancy force due to the gaseous character of the medium in which it is located. This additional force is described by the Yukawa potential present in the effective galactic potential, which is called the *buoyancy potential.*

From equation 1 one obtains the expression for the galactic circular velocity as a function of radius

$$v_{circ}(r) = \left\{ \frac{GM}{r} \left[1 + \beta\left(1 + \frac{r}{r_0}\right) e^{-r/r_0} \right] \right\}^{1/2} . \qquad (2)$$

In Figure 1, we show the rotational velocity of a mass element in a galaxy that obeys the potential given by eq. (1). The velocity is given by equation 2, and the scale parameters are properly chosen to give rise to the rotation curve shapes depicted in the figure. We represent M by a Plummer model (a polytrope of index 5, essentially a very centrally concentrated spherical mass distribution, which is convenient to represent a point mass), and express it by its total mass, in arbitrary units. The parameters β and r_0 are also expressed in arbitrary units. The basic model has $M = 1$, $\beta = -1$ and $r_0 = 1$; each panel in Fig. 1 has one of these parameters changed, while other two are retained at their basic vaues.

As we have mentioned above, one should look for a way of *pulling down* the Keplerian rotation curve obtained with the combination of a luminous disk plus M/L values like those derived from binary galaxy studies. Figure 2 illustrates such a process which is performed by the model proposed through eq. (1). The figure shows two panels with a sequence of different values for the scale parameter r_0. As r_0 diminishes, the effective rotation approaches the Keplerian curve (no buoyancy effect at all).

b) *Phenomenological Counterpart*

The apparent *ad hoc* nature of the proposed model can be weakened by a phenomenological counterpart. A plausible description of the model is given as follows. Consider a galaxy as sketched in Fig-

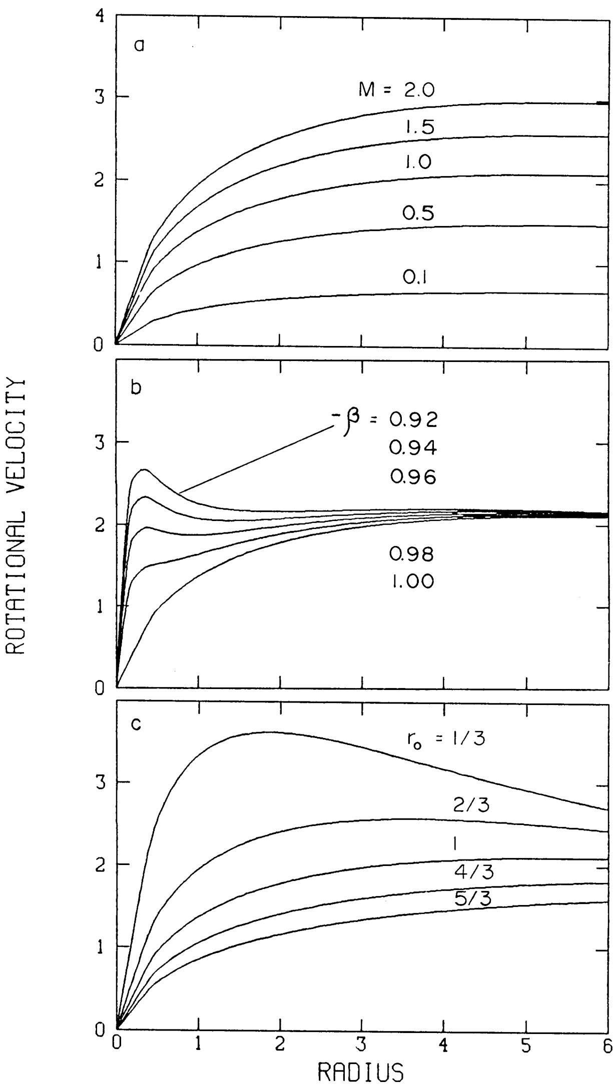

Fig. 1. Rotation curves obtained with the buoyancy potential model galaxy [eqs. (1) and (2)]. The basic model has total mass $M = 1$, $\beta = -1$ and $r_0 = 1$. In panel (a) the galactic mass varies; in (b) β varies; and in (c) r_0 varies. The three panels illustrate the wide range of rotation curve shapes allowed by the model.

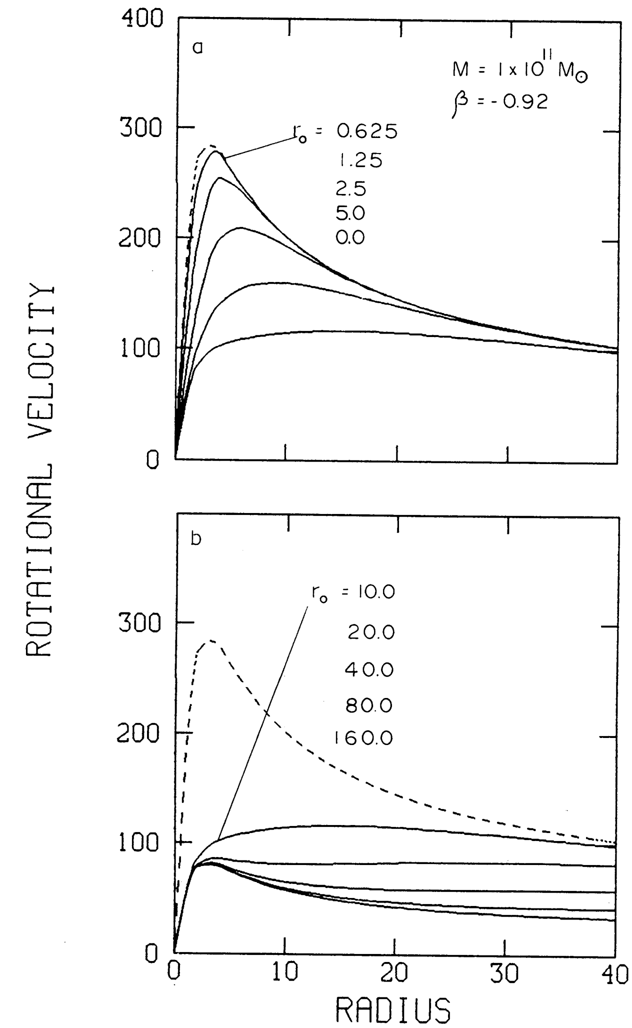

Fig. 2. The model presented here has $M = 1 \times 10^{11}\ M_{\odot}$, $\beta = -0.92$, and different values for r_0. In panel (a), from the top solid curve we have $r_0 = 0.625, 1.25, 2.5, 5.0, 10.0$ kpc. Panel (b) follows with $r_0 = 10, 20, 40, 80, 160$ kpc. The dashed curve is the usual Keplerian rotation curve, without the effects of the buoyancy potential (velocities in km s^{-1}, radii in kpc).

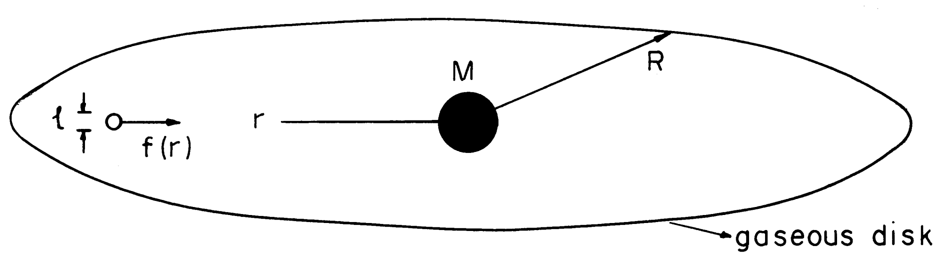

Fig. 3. The model galaxy is shown as a gaseous disk of radius R surrounding the bulk of the galactic total mass M, located in its center. A representative "bubble" element, inside the disk, with scale-length l ($\ll R$) is located at a distance r from the galactic center. The net force per unit volume acting on the bubble is $f(r)$.

ure 3. We assume the existence of "bubbles" of gas inside the underlying gaseous disk, regardless of their origin. This picture is not far from a real spiral galaxy. In Figure 3 we show a representative bubble, situated at a distance r from the galaxy center. The mean density of a bubble is given by $\rho_{ig}(r)$. The external gas, i.e., the underlying gaseous disk at that position has a density equal to $\rho_{eg}(r)$. The net gravitational force per unit volume that acts on the bubble, with a buoyancy component due to the presence of density gradients, is

$$f(r) = \frac{GM}{r^2}\left[\rho_{ig}(r) - \rho_{eg}(r)\right]$$

or $\qquad , \qquad (3)$

$$f(r) = \frac{GM}{r^2}\rho_{ig}(r)\left[1 - \frac{\rho_{eg}(r)}{\rho_{ig}(r)}\right]$$

where M is the galaxy mass. When $\rho_{ig} = \rho_{eg}$, that is, when the medium has no density gradients, the net force is zero; a bubble element is either at rest or is moving with constant speed. In a rotating system, the net force is balanced by the centrifugal force, and a rotation profile can be derived [eq. (7)].

The underlying gaseous disk is assumed to have an exponential density distribution

$$\rho_{eg}(r) = \rho_{0e} e^{-r/r_{0e}} \quad . \qquad (4)$$

Here, ρ_{0e} and r_{0e} are scale parameters. The internal (bubble) gas density has a radial distribution given by

$$\rho_{ig}(r) = \frac{\rho_{0i}}{1 + r/r_{0i}} \quad , \qquad (5)$$

with ρ_{0i} and r_{0i} being also scale parameters. This expression constitutes essentially a truncation of high order terms of the series representation of the density distribution of the underlying external disk [eq. (4)], and where we assume for generality different scale parameters.

The choice of these density profiles is rather arbitrary. The main reason for the adoption of these specific distributions is that they lead to an effective gravitational potential that can be expressed similarly to eq. (1) (see below).

The acceleration of a bubble, sitting at a distance r from the galaxy center, is obtained by means of Newton's Second Law together with eqs. (3), (4) and (5). This calculation yields

$$\ddot{r} = \frac{GM}{r^2}\left[1 - \frac{\rho_{0e}}{\rho_{0i}}\left(1 + \frac{r}{r_{0i}}\right)e^{-r/r_{0e}}\right] . \qquad (6)$$

For bubbles rotating about the galaxy center, the circular velocity at r is given by

$$v_{circ}(r) = \left\{\frac{GM}{r}\left[1 - \frac{\rho_{0e}}{\rho_{0i}}\left(1 + \frac{r}{r_{0i}}\right)e^{-r/r_{0e}}\right]\right\}^{1/2} . \qquad (7)$$

Making $\rho_{0e}/\rho_{0i} = -\beta$, and $r_{0e} = r_{0i} = r_0$, the force field given by eq. (6) is easily shown to be derived from the potential given by eq. (1) and eq. (7) reduces to the same expression of eq. (2). Thus, we have shown that there is a plausible physical explanation for the toy model proposed at the beginning of this section.

III. DISCUSSION AND CONCLUSION

We have presented an alternative view of flat rotation curves of spiral galax-ies, in which the main suggestion is that M/L values valid for these systems are those primarily obtained from dynamical studies of binary galaxies. Such values are consistently higher than usual values by a factor of 10 – 15. The result is that the observed H I rotation curves are located "below" the Keplerian luminous rotation curve rather than "above" it. The correct approach is, then, to search for mechanisms that provide a way of *pulling down* the rotation profile to the observed levels. The model galaxy represented by eq. (1) is meant to provide such a mechanism.

Incidentally, the model advocated here has the same mathematical description of the modification of Newtonian attraction suggested by Sanders (1984, 1986, hereafter FLAG, *finite length-scale anti-gravity*), with the great difference that while in FLAG the equivalent constants to β and r_0 are "universal" scale parameters, here both of them are intrinsic galactic parameters and in principle are different from galaxy to galaxy, i.e., each galaxy is characterized by its own set of scale parameters.

It must be pointed out that FLAG is unable to explain one of the most important observed features of spiral galaxies, the Tully-Fisher relation (Tully and Fisher 1977), and hence is inadequate as a model for galactic dynamics (Sanders 1990). The use of FLAG made here, refers only to its mathematical structure.

It is obvious that the potential given by eq. (1) has all of the interesting features of the FLAG potential, e.g., the wealthy variety of flat and non-flat rotation curves that can be obtained according to the given set of scale parameters. It should be also pointed out that, unlike FLAG, the gravitational constant here is the usual one (G), and that Newtonian dynamics is entirely preserved. In FLAG, due to the new potential component (the Yukawa potential shown in the previous section), the "effective" gravitational constant is $G_\infty = G_0/(1 + \alpha)$, where α (here called β) is the coupling constant for this additional component of gravity. In the context of FLAG, α is negative (the added gravitational component is a repulsive one), and approximately equal to unity, that is to say, G_∞ can be much larger than G_0. In fact, with FLAG's best fitting value of α (-0.92), G_∞ is $1.25 \times G_0$. Now, in the model presented here we argue that the M/L values should be considered as those given by binary galaxy studies, i.e., 10 – 15 times larger than the usual M/L values (adopted in the context of the dark halo hypothesis, and in FLAG as well). The role of increasing G in FLAG is taken here by the larger values of M/L, which has an observed justification in the dynamics of binary galaxies. The calibration galaxy used by Sanders to determine FLAG's parameters for NGC 3198 (see also van Albada *et al.* 1985) can be used in our framework with the modification of the M/L value adopted by him (given by van Albada *et al.*) and, of course, adopting the usual gravitational constant. Instead of M/L = 3.6 we take M/L = 45, consistent with binary spiral galaxy observations, $\beta = -0.92$ and $r_0 = 24$ kpc, and obviously we get the same result presented by Sanders (1986) in his Figure 1: an excellent fit to the observed rotation curve.

Finally, it is not trivial from our model to predict the shape of the Tully-Fisher relation. Rather, from the observed Tully-Fisher relation one should be able to draw conclusions about the behaviour of the intrinsic parameters β and r_0, among spiral galaxies of different luminosities.

In conclusion we suggest that in view of the presence of gas component in the galactic mass distribution, the gravitational potential of a spiral galaxy is well described by a two-component potential. One component has a Keplerian form, and the other, a Yukawa form, being due to buoyancy effects in the galactic disk. The buoyancy component arises because there are radial density gradients in gaseous disks of spiral galaxies. The phenomenological model put forward in the previous section is just a tentative physical description of the postulated potential given in eq. (1).

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